Advanced Reciprocating Engine Technology for Power Generation in California

(Review of ARES Consortia @ SwRI)

Southwest Research Institute

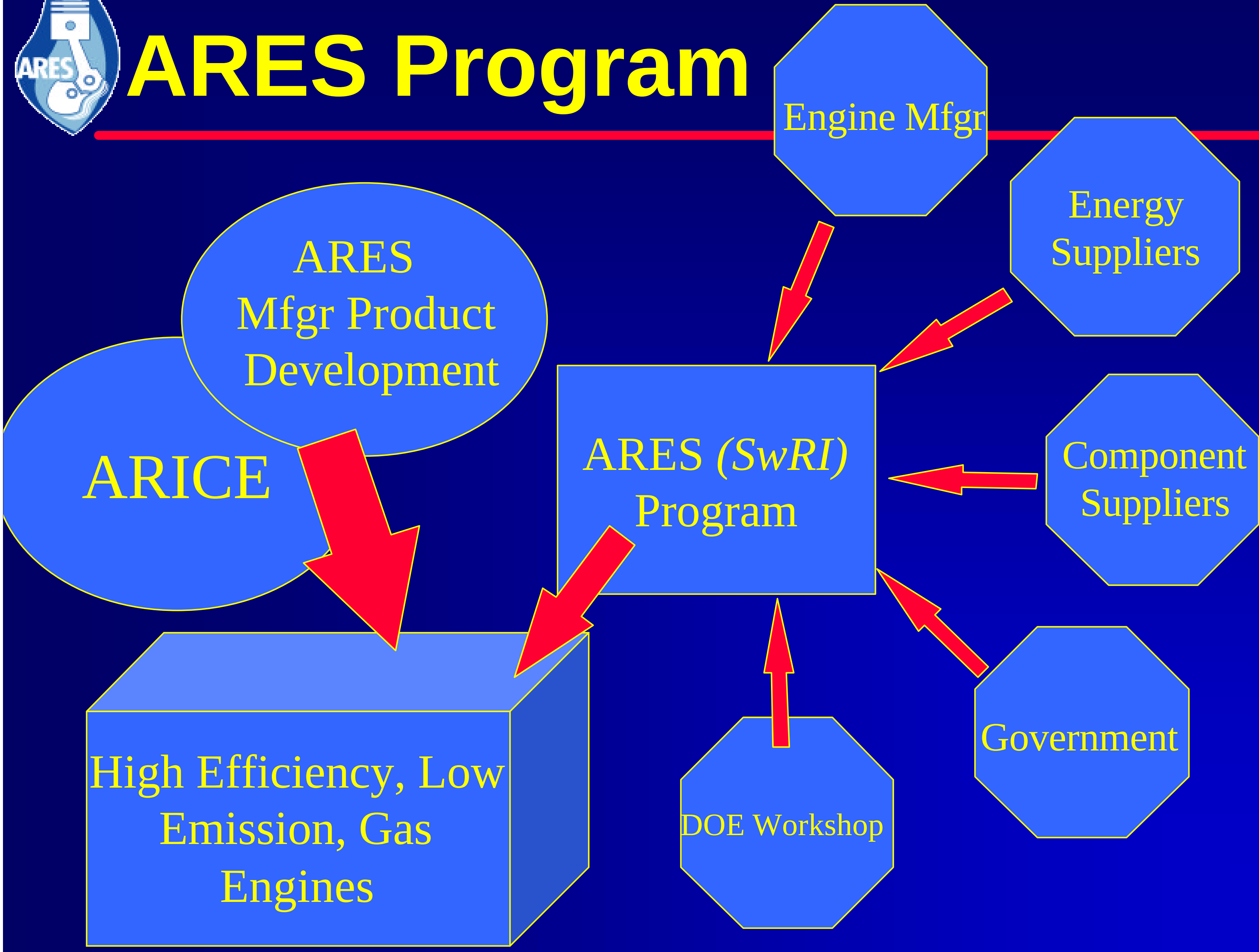
July 2001

Advanced Reciprocating Engine Systems

What is ARES?

- **Generic Acronym**
  - **Advanced Reciprocating Engine Systems**
- **Cooperative Research Program (CRP) organized by SwRI - "precompetitive technology" focused on Stationary Natural Gas Engines for Power Generation**
- **Continues to be an acronym for Joint Industry DOE programs for development**

ARES Program



Program Members

- Department of Energy
- Gas Research Institute
- Caterpillar
- Cooper Energy Services
- Cummins
- Waukesha Engine Division
- Southern California Gas Company
- Altronic
- Champion
- Woodward

ARES (SwRI) - Objectives

- Identify and develop key technology in a precompetitive program for high efficiency, low emission, natural gas, reciprocating engines.
- Support development of competitive products with manufacturers.
- 50% Efficiency
- 5 ppm NO_x AT 15% O_2 (~0.05 g/bhp-hr)
- THC - Maintain Current Level
- HAPs - Maintain Current Level
- Technology
  - Must Reduce Cost of Electricity
  - Must Not Impact CHP Applications
  - Maintain Durability and Reliability

Barriers to High Efficiency

- Knock
- In-cylinder heat loss
- Burn rate
- Combustion inefficiency
- Frictional losses
- Pumping losses
- Heat loss in exhaust port and manifold
- Inefficient exhaust energy recovery
- Mechanical strength/design
- NO_x Emissions

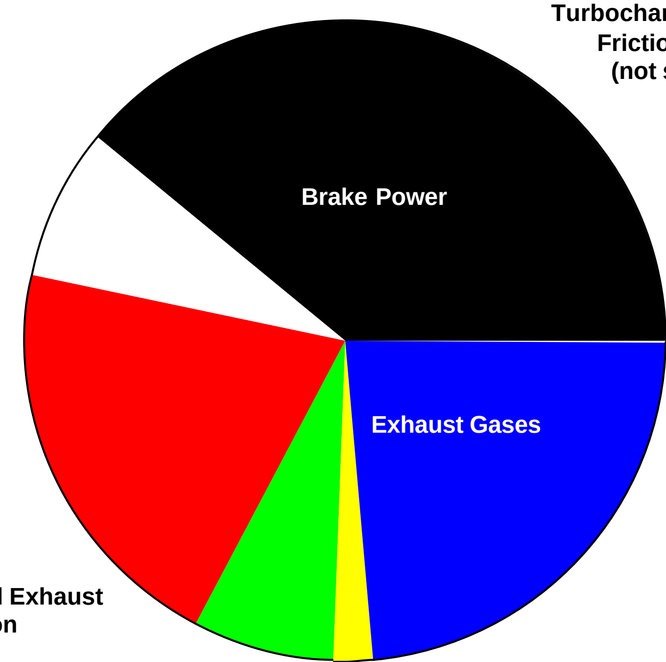
Program Direction

- High Efficiency Will Require High BMEP
- Knock Limitations Must be Overcome to Achieve High BMEP
- Reduction in Energy Losses will Increase Efficiency
- Dilute Air-Fuel Mixtures Required for Low NO_x
- Favorable Ignition and Combustion Dilute Mixtures a Necessity
- Aftertreatment Required

Funded Tasks

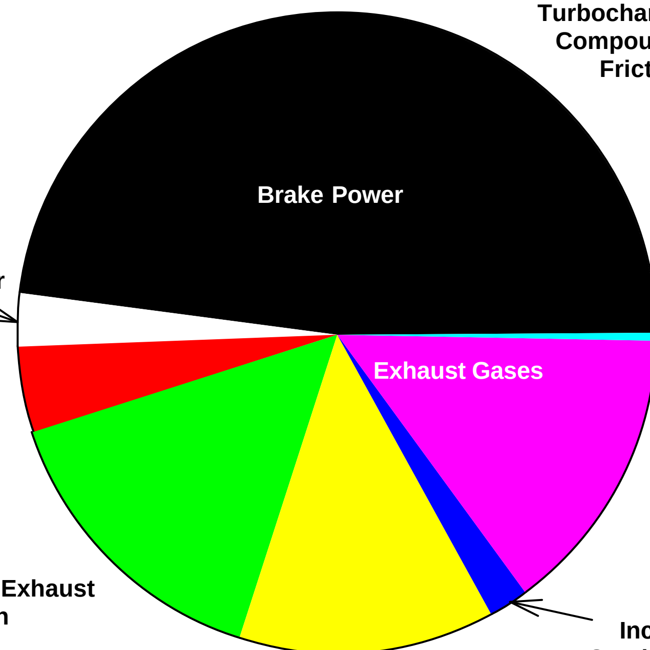
- Technical Path Evaluation
- Knock Modeling
- High BMEP Engine Development
- Exhaust Aftertreatment
- Ignition System Development
- Direct Water Injection
- Micro-pilot Ignition
- Stoichiometric/EGR
- Not funded: HCCI, HPDI, Sparkplug life, laser ignition, Syngas

Technical Path Evaluation



Baseline Engine Energy Balance

ARES 50 Percent BTE Engine Energy Balance



Advanced Reciprocating Engine Systems

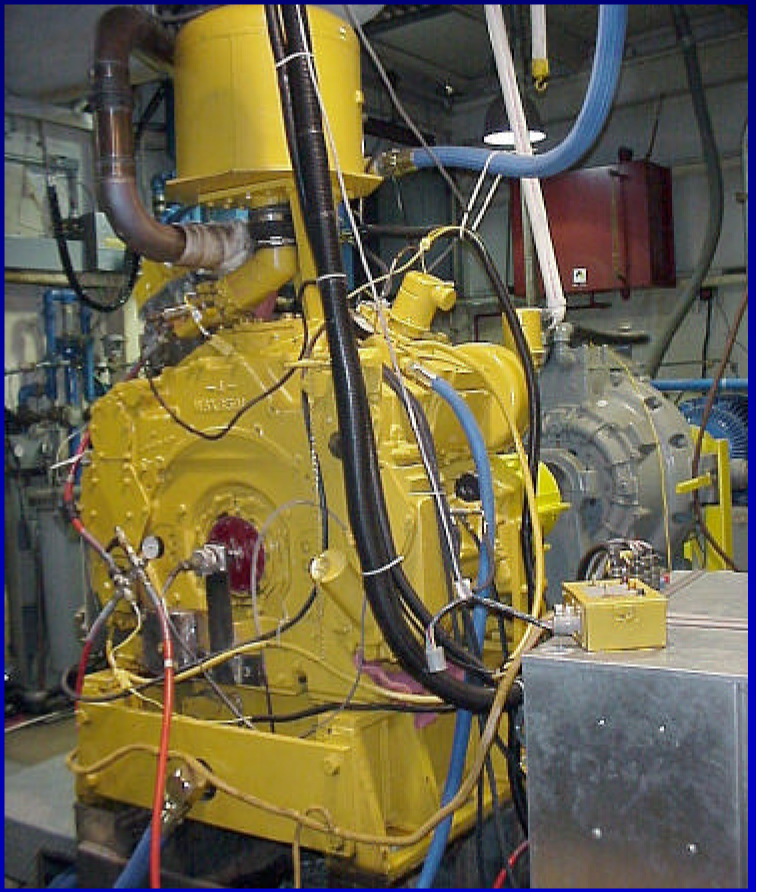
Summary

Approximate 50% BTE Engine

	Description
Miller Cycle	X.X Expansion Factor
Turbo-Compounding	XX% turbine efficiency XX% gear train efficiency
Low Heat Rejection Exhaust System	XX% heat loss reduction
Low Friction/High BMEP	AA% to BB% mechanical efficiency
Burn Rate	CC degree to DD degree 10 to 90% burn duration
Flow Improvement	EE% Improvement
Two-Stage Compression w/	FF% compressor efficiency per stage,

High BMEP Engine Development

- **Objective**
  - **Conduct Engine Testing of Methods for Increasing BMEP to Improve Efficiency**
  - **Verify Modeling Results From Technical Path Evaluation & Knock Mitigation Strategy Evaluation**
  - **Identify Enabling Technology for High BMEP Operation**
- **Approach**
  - **Use Single Cylinder Engine as Test Bed for Alternative Cycles, Ignition Systems, Direct Water Injection, EGR, Combustion Chamber Design for Knock Tolerance**

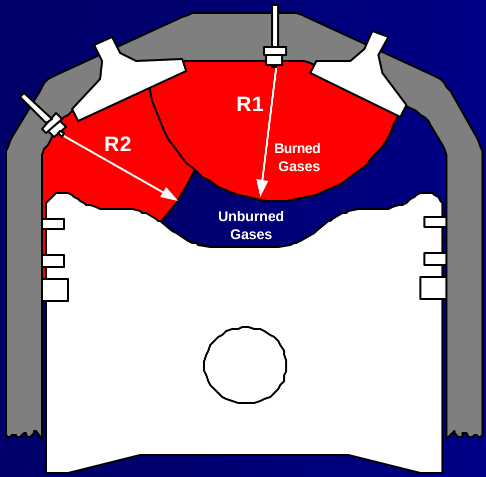


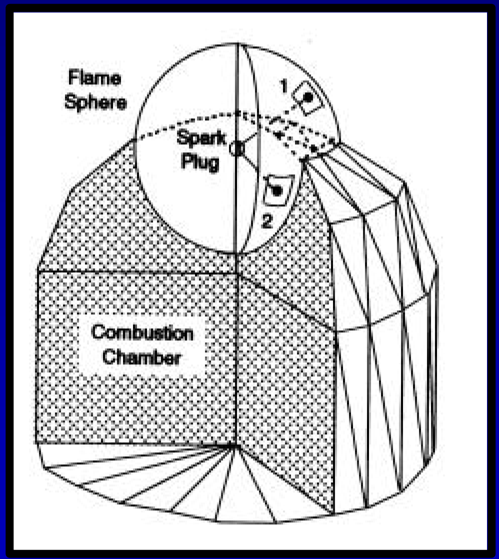
Variables Impacting Engine Performance

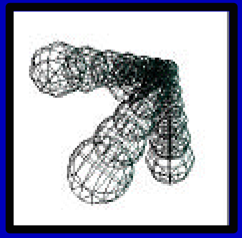
	RPM	IMEP	BMEP	Equivalence Ratio (Phi)	Expansion Factor (EF)	Expantion Ratio (ER)	Peak Cylinder Pressure (PCP)	50% Burn Location (CA50)	$CA50^2$	Burn Duration (B1090)	Exhaust Port Temp. ($T_{Ex.Port}$)	Temperature at Ignition (T_{ign})	Squish Velocity (V_{sq})	Combustion Bowl Volume (V_{bowl})	R-Square
h_{mech}	⇩	⇧					⇩								0.8646
h_{pump}	⇩				⇧										0.9622
h_{cycle}				⇩		⇧		⇩	⇩	⇩					0.9003
h_{comb}						⇩	⇧				⇧				0.8437
NO_x			⇧	⇧	⇩	⇧		⇩							0.9222
B1090				⇩								⇩		⇩	0.8487
PCP		⇧		⇩		⇧		⇩							0.9836
Exhaust Port Temperature ($T_{ex.port}$)	⇧			⇧		⇩		⇧							0.9479

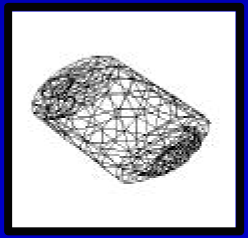
Knock Modeling

- Correlated with Experimental Data
- Chamber shape and ignition effects



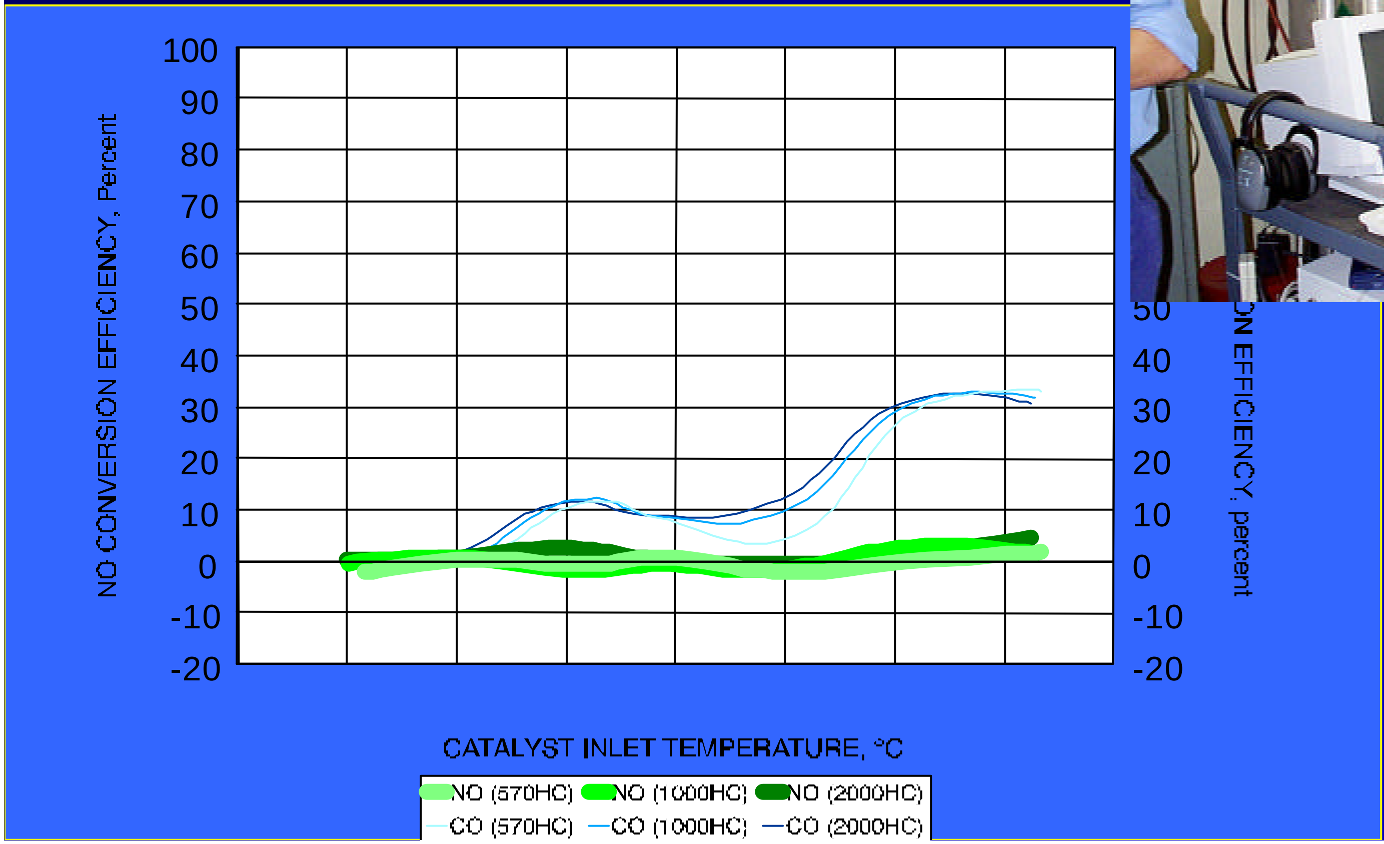






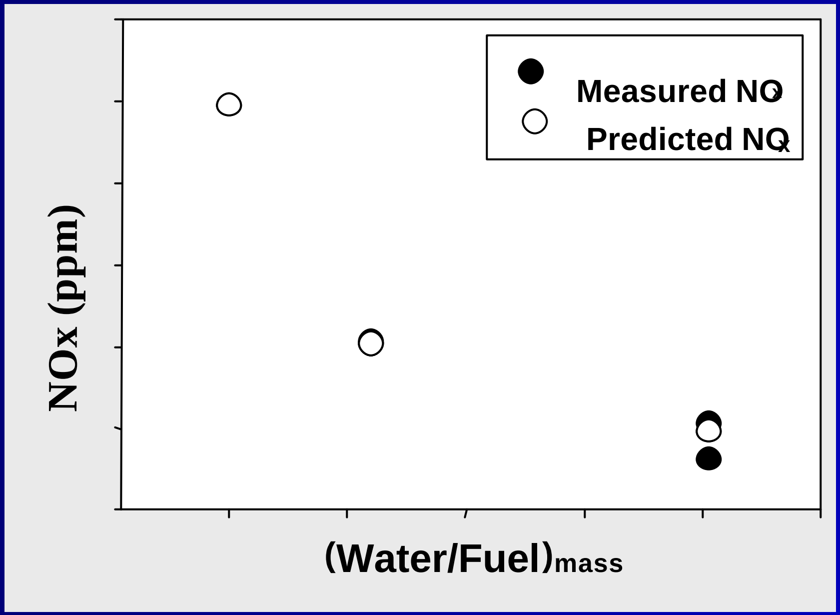
Exhaust Aftertreatment
Lean NO_x Catalysts

- **Promising formulations from Literature review proved non-effective**
- **SCR Demo showed NO_x eff. > 90%**
- **Non-Thermal Plasma extends low temperature operation of SCR**



Direct In-Cylinder Water Injection

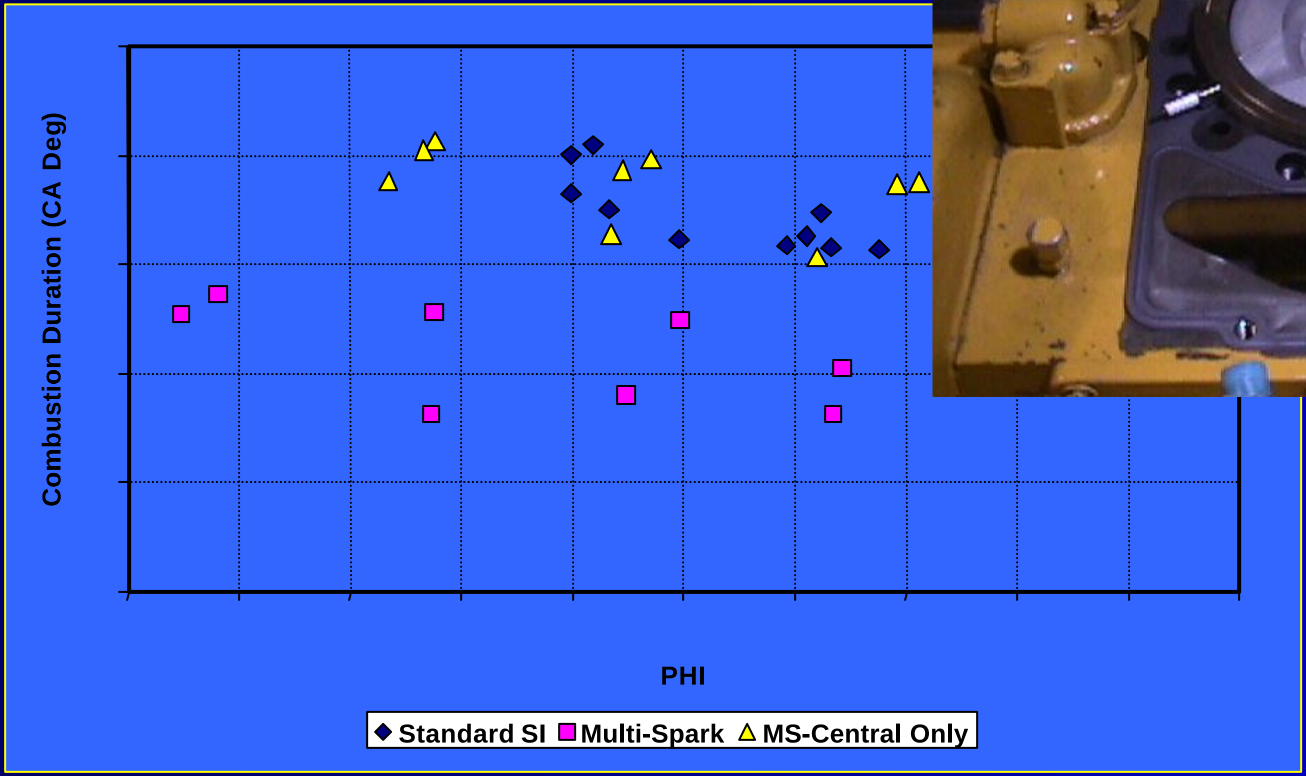
- Microfine Spray of water simultaneously:
  - Improves Knock Tolerance
  - Reduces NO_x Emissions
  - Allows Increased BMEP for Increased Efficiency
- Use of water increasingly common in large diesel engines

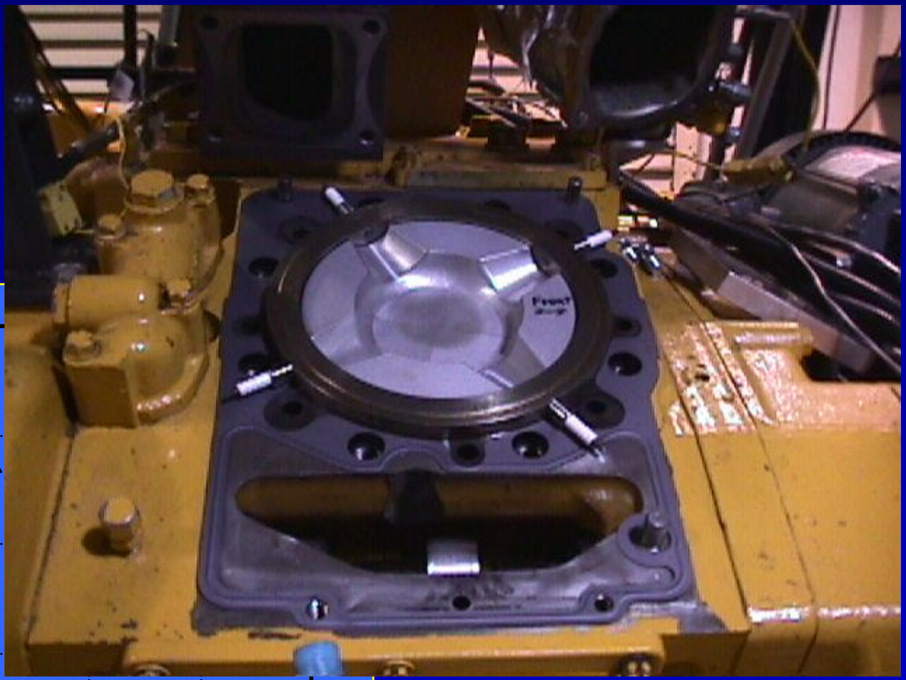


Advanced Reciprocating Engine Systems

Ignition System Development

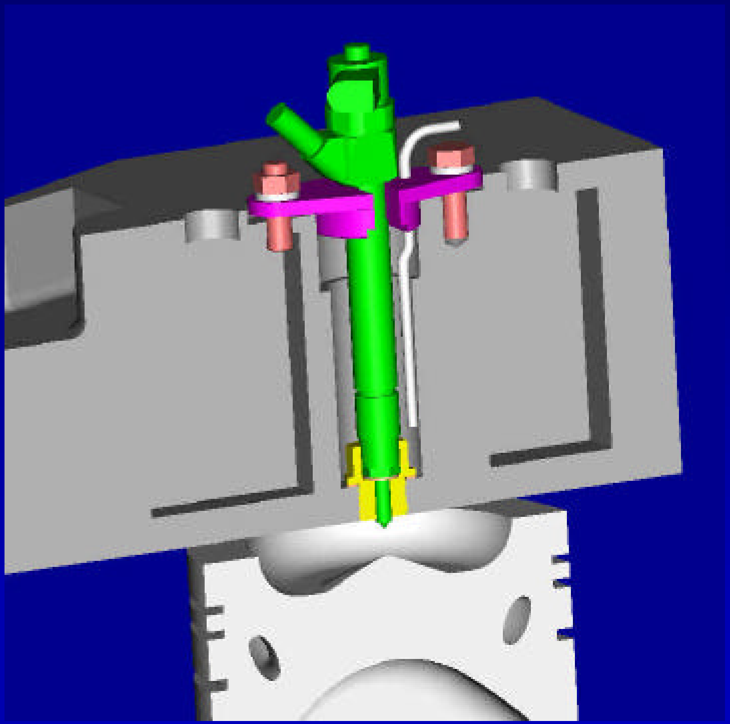
- **Multiple Spark Ignition provides desired BMEP improvement and combustion duration**





Micro-Pilot Ignition

- **Objective**
  - **Develop an Understanding of Tradeoffs for Micro-pilot Ignition Relative to Other Ignition Systems**
- **Approach**
  - **Literature Review**
  - **Engineering Analysis of Injection System Requirements for Large Bore Engines**
  - **Extensive engine testing with HPCR and full authority control**
- **Summary**
  - **Pilot Ignition Can Provide Improved Performance and Lower NO_x Emissions**



Stoichiometric Engine w/EGR

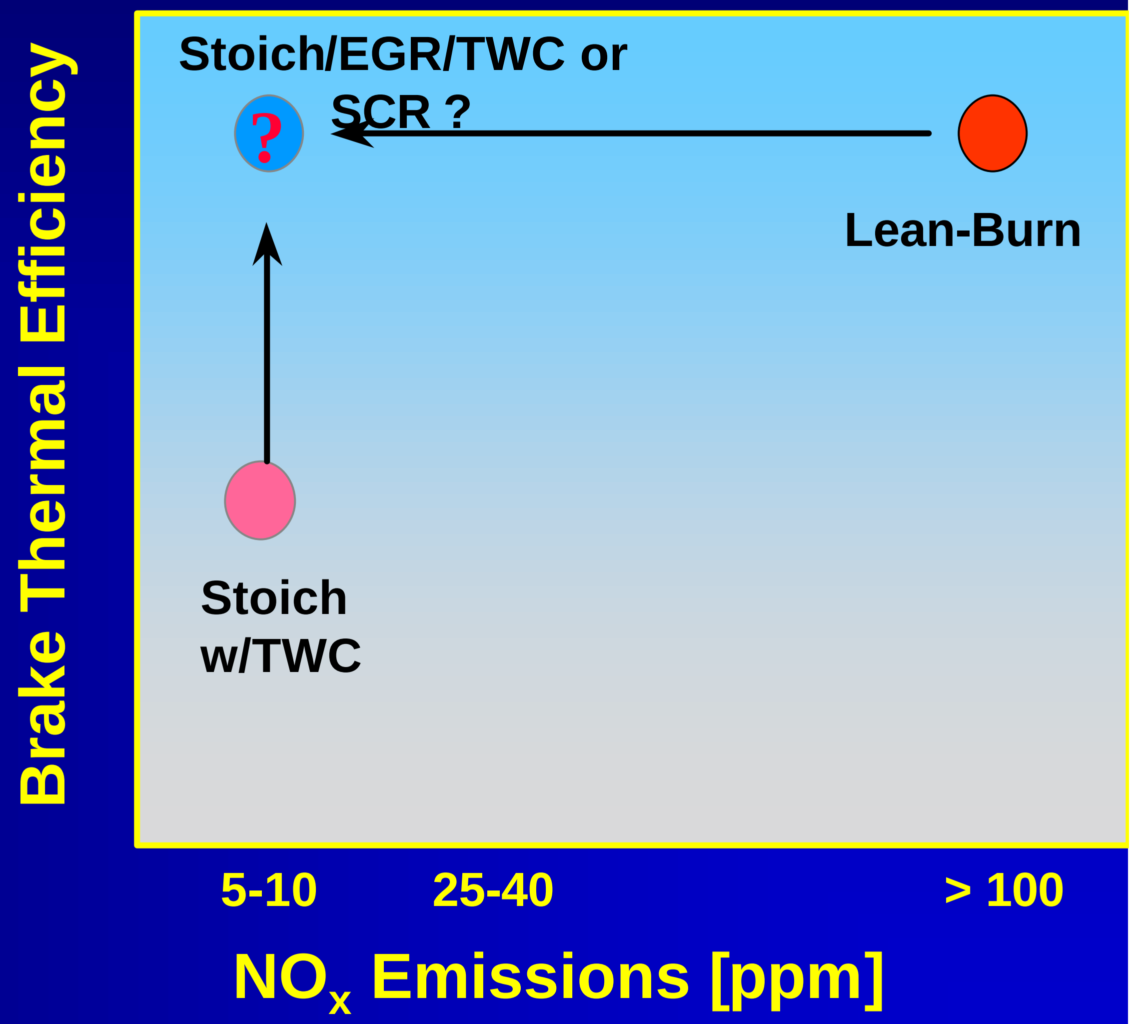
- Exhaust Temperature = Lean-Burn
- Use Lean-Burn Comp. Ratio & Boost
- Increased BMEP over Stoichiometric
- Engine-Out NOx Reduced
- Allows Variability in A/F Ratio Control
- Three-Way Catalyst Used for <15 ppm NOx
- Much Cheaper than SCR on Lean-Burn
- Low CO and Air Toxics
- Micro-Pilot, Syngas extend EGR tolerance

ARES…ARICE

Clean Power Generation Products that Enhance the Public Good and Make Economic Sense

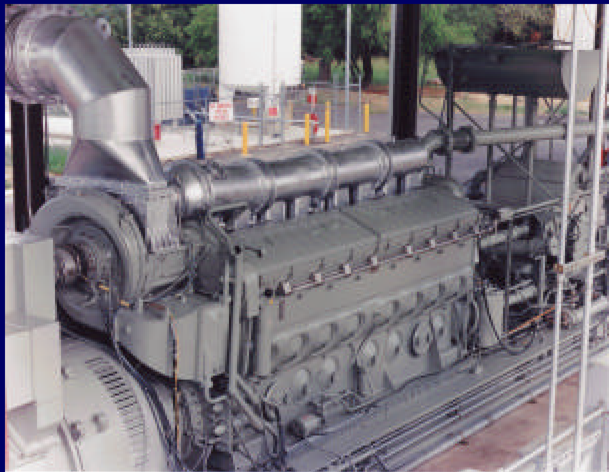
NO_x Reduction Technology Comparison

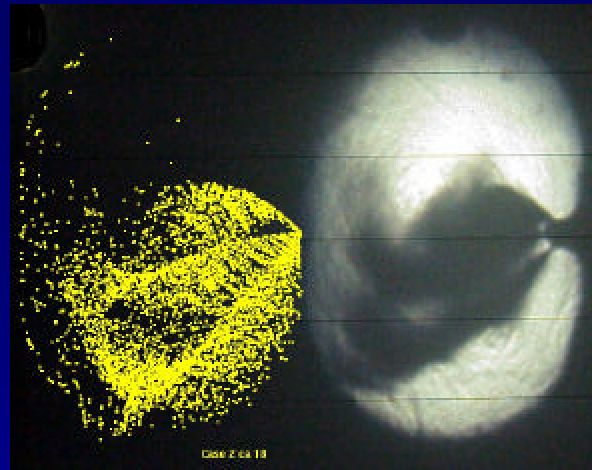
- ARICE include focus on marriage of engine and aftertreatment technology
  - Durability
  - Efficiency
  - Cost
- Stoich/EGR/TWC possible short term solution

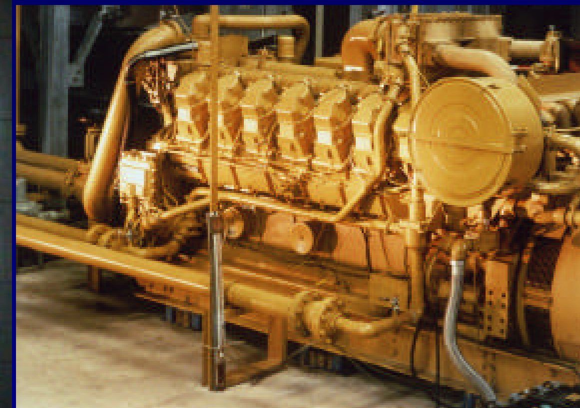


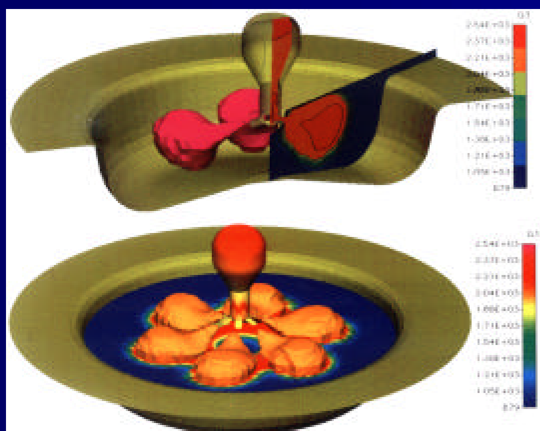
ARICE Technologies??

- Departure from present technology. Non-traditional approaches? (HCCI/Fuel Treatment/Combustion Chamber Design)
- Advanced controls absolute necessity
- BMEP increase required
- Turbomachinery improvements needed
- Aftertreatment required









Contact Information

James Cole

210-522-5473

jcole@swri.org